Quarterly Reports on the State of the Ocean: Meridional Heat Transport Variability in the Atlantic Ocean

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Project Summary

Goal: To contribute to the assessment of the state of the ocean by providing quarterly reports on the meridional heat transport in the Atlantic Ocean. This heat transport is directly related to the role that this basin plays in the meridional overturning circulation (MOC) and is an important benchmark for integrated air-sea fluxes and numerical model performance.

Project Output: "State of the ocean" quarterly estimates of meridional oceanic heat transport in the center of the subtropical gyres in the North and South Atlantic. This project funds the development of a methodology to estimate heat transport variability using data collected along two high density XBT lines operated by AOML, satellite data (altimeter and scatterometer), wind products from the NCEP reanalysis and products from general circulation models. Quarterly reports are posted on the AOML web site.

General Overview: The Atlantic Ocean is the major ocean basin involved in large-scale northward transports of heat typically associated with the meridional overturning circulation (MOC) where warm upper layer water flows northwards, and is compensated for by southward flowing North Atlantic Deep Water. This large-scale circulation is responsible for the northward heat flux through the entire Atlantic Ocean. Historical estimates of the net northward heat flux in the vicinity of its maximum, which occurs in the North Atlantic roughly at the latitude of the center of the subtropical gyre, range from 0.9 PW[1] to 1.6 PW, while estimate in the 30°S to 35°S band are even more uncertain, ranging from negative to more than 1 PW. While much of this variability may be a consequence of the different methods used to estimate the heat transport, natural variability cannot be ruled out. The importance of this heat transport to the world climate together with the possibility of monitoring its variability motivates this project.

AOML collects XBT data on two lines spanning the subtropical oceans: in the North Atlantic since 1995 (quarterly repeats) along AX7 running between Spain and Miami, Florida and in the South Atlantic since 2002 (twice per year until 2004 and quarterly thereafter) along AX18 between Cape Town, South Africa and Buenos Aires, Argentina. These data capture the upper limb of the MOC transport. In the North Atlantic much of the northward transport is confined to a strong boundary current through the Florida Straits, where XBT data can also be usefully augmented with other data from the NOAA/OCO funded Florida Current transport program.

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[1] PW is PetaWatt or 10^{15} Watts, a unit of power commonly used for ocean heat transports.

Heat transports have already been successfully computed using XBT data (Roemmich et al, 2001), however the methodology for estimating the transport can be improved. In particular, as density is essential for the flux estimates, results depend on how well salinity profiles can be estimated to complement the XBT data and on how well the profiles can be extended to the bottom of the ocean. Improving these estimates to achieve more accurate fluxes is an essential part of this project, as is a careful quantitative assessment of the accuracy of the resulting fluxes.

Methodology: Northward mass, volume, and heat transport through a vertical plane

$$M = \iint \rho v \, dxdz \qquad V = \iint v \, dxdz \qquad H = \iint \rho c_p \theta v \, dxdz$$
$$[\mathrm{Kg/s}] \qquad [Sv = 10^6 m^3 / s] \qquad [PW = 10^{15} Watts]$$

can be estimated directly from observations. The northward velocity v can be treated as a sum of three terms: (i) a geostrophic contribution (thermal wind equation) relative to a prescribed reference level, (ii) an ageostrophic part modeled as Ekman flow, and (iii) a barotropic part define as the velocity at the reference level. Density ρ can be obtained from XBT data if salinity is accurately estimated and data are extrapolated to the ocean bottom.

Preliminary estimates of mass and heat transport have been obtained from temperature profiles collected along AX07 and AX18 high-density lines using Sippican T-7 XBT probes, which typically provide data to 800 m or deeper. Salinity was estimated for each profile by linearly interpolating the closest of Levitus' climatological mean salinity and temperature profiles to the XBT temperature and the climatological profiles were used to extend the data to the bottom. In computing geostrophic velocities, a reference level, based on previous work in the literature and on what is known about the circulation, was prescribed just below the northward flowing Antarctic Intermediate Water (σ_0=27.6 kg m^{-3} in the North Atlantic and σ_0=27.4 kg m^{-3} in the South Atlantic). Within strong flows such as the Florida Current or the Malvinas Current where no level of "no motion" can be found, the transport must be specified (e.g. by the mean value of the Florida Current, etc.). The velocity at the reference level is adjusted so that the net mass transport across the section is zero using a single velocity correction for each section. Typically, values of this correction ranged from 10^{-4} to 10^{-6} m s^{-1}.

Accomplishments

Products Delivered: Quarterly reports were designed that show the estimated heat transport for each high density XBT section along the AX7 and AX18 lines (Figure 1 and 2) and are posted quarterly on AOML's state of the ocean web site at http://www.aoml.noaa.gov/phod/soto/mht/index.php. Each figure shows: the position of the most recent XBT transect (red) and the position of the all the transects completed to date (blue) (Top left panel); the temperature section corresponding to the last section (top right panel); the time series of the obtained values for the different components of the heat transport (bottom left) and the annual cycle of the heat transport components (bottom right).

Values of heat transport are given in PW (1 PW = 10^{15}W). One PW is equivalent to the amount of electricity produced by *one million* of the largest nuclear power plants in existence today (the largest nuclear plants produce about 1 gigaWatt of electrical power).

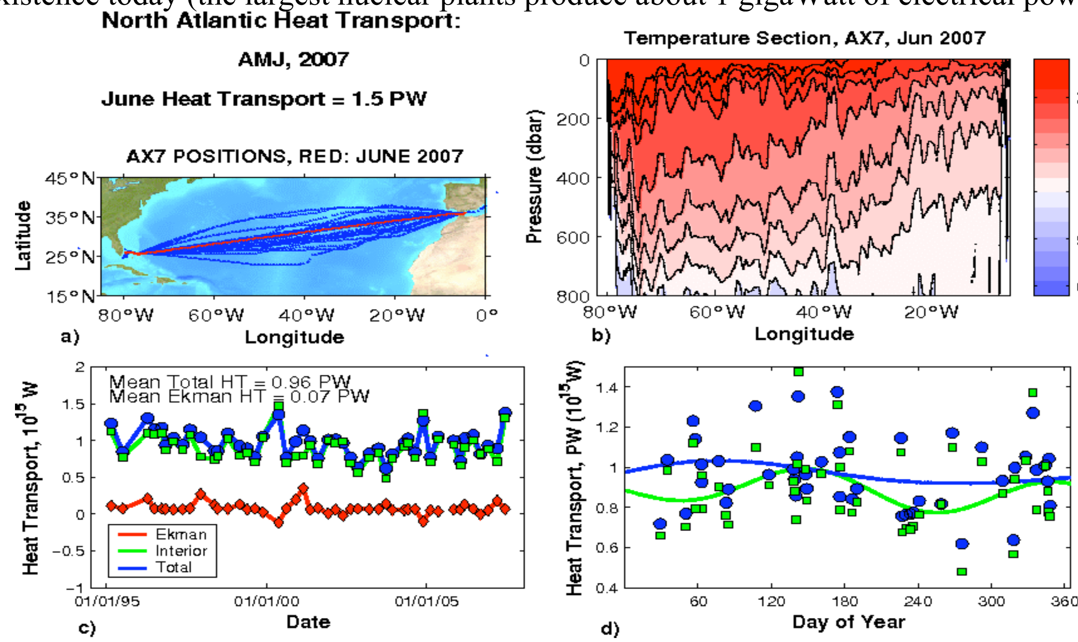

Figure 1: Report for the April-May-June quarter of 2007 for North Atlantic Meridional Heat transport along the AX7 high density XBT line. Transport results based on June 2007 XBT section (positions shown in top left, temperature section shown in top right). Heat transport estimates were decomposed into the geostrophic (interior) and Ekman components and their total (lower left). Heat transports contain an insignificant seasonal signal (lower right) with only a slight suggestion that spring sections have a higher heat transport than fall sections. The heat transport during this quarter was significantly higher than the mean heat transport and appears to alter the recent trend towards reduced heat transports.

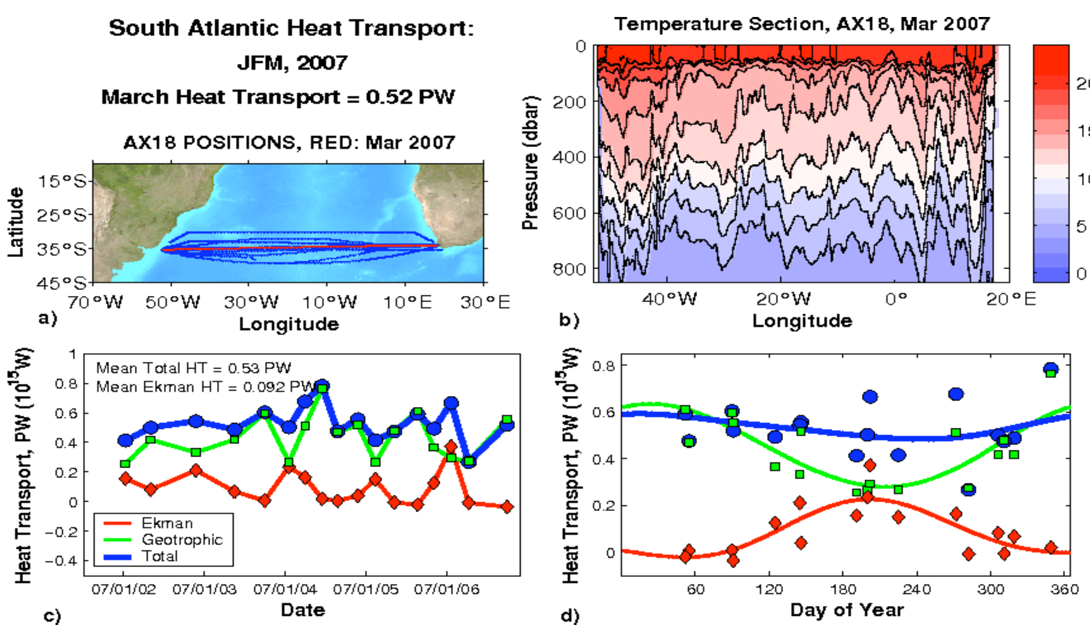

Figure 2: Report for the January-February-March quarter of 2007 for South Atlantic Meridional Heat transport along the AX18 high density XBT line. Transport results based on March 2007 AX18 XBT section (positions shown in top left, temperature section shown in top right). Heat transports were

estimated using a shallow (green squares) and deep (red diamonds) reference level (lower left). Total heat transports demonstrate no significant seasonal signal because the seasonal signal in the Ekman layer is directly out of phase with the geostrophic signal (lower right). The July heat transport was close to the mean transport observed over the past four years.

Scientific Findings:

This year, Thacker (2007) and Thacker and Sindingler (2007) published two studies of how to estimate Salinity for each XBT by using available Argo and CTD profiles. Results from this work allow us to improve the estimation of salinity by using a spatially dependent function where salinity depends on the Temperature and Depth of the XBT observation.

In the North Atlantic, the heat transport was found to vary on inter-annual time scales from 0.8 ± 0.2 PW at present to 1.2 ± 0.2 PW in 1996 with instantaneous estimates ranging from 0.6 to 1.6 PW (Figure 1). Heat transport due to Ekman layer flow computed from annual Hellerman winds was relatively small (only 0.1 PW). This variability is entirely driven by changes in the interior density field; the barotropic Florida Current transport was kept fixed (32 Sv[2]). At low frequencies, North Atlantic heat transport variations were found to correlate with the Atlantic Multidecadal Oscillation (AMO) as shown in Figure 3.

Improvements to these estimates should include (i) time varying Florida Current transports and wind fields, (ii) improved salinity estimates and extrapolations to the bottom, and (iii) improved error estimates that reflect the effect of the initial reference level, the wind field variability, the importance of barotropic flows, and the uncertainties of the salinity estimates and the extrapolations.

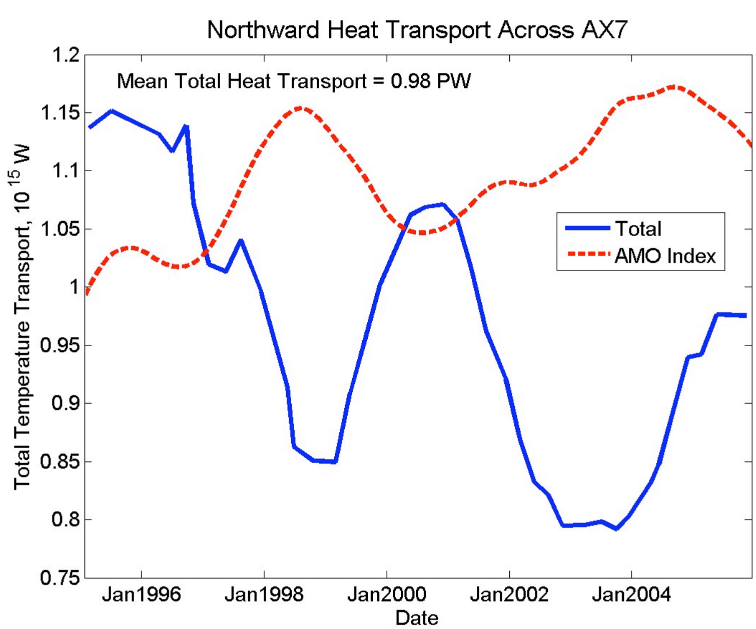

Figure 3: Time series of total heat transport in the center of the subtropical gyre in the North Atlantic Ocean along the XBT lined designated AX7. In the North Atlantic, there has been an apparent decrease in heat transport over the past 10 years (solid blue). Heat transport is inversely related to the Atlantic Multidecadal Oscillation (AMO) Index (red dashed)

[2] Sv is a Sverdrup or 10^6 m^3/s, a unit commonly used for ocean volume transports.

South Atlantic: The methodology described above was applied to the South Atlantic data and an intensive study of the errors was completed (Baringer and Garzoli, 2007). The procedure is tested using CTD data collected during the World Ocean Circulation Experiment (WOCE) along the 30°S hydrographic transect (A10) and the output from a numerical model. The results indicate that the methods described here can provide heat transport estimates with a maximum uncertainty of ±0.18 PW. Most of this uncertainty is due to the climatology used to estimate the deep structure and issues related to not knowing the absolute velocity field and most especially characterizing barotropic motions. Nevertheless, when the methodology is applied to temperatures collected along 30°S (A10) and direct model integrations, the results are very promising. From analysis of the numerical model this study also found that ageostrophic non-Ekman motions can contribute less than 0.05 PW to heat transport estimates in the South Atlantic.

Garzoli and Baringer (2007) applied extended these results by applying the method to the fourteen high-density XBT AX18 sections collected between July 2002 and May 2006 to compute the meridional heat transport in the South Atlantic. The integrated volume transport yields a mean value for the total transport east of the Walvis ridge of 28 Sv, 19 Sv for the Brazil Current (between 0 and 800 m) and -9 Sv for the DWBC (2500 to 6000). These values are agreement with the previous calculations obtained from direct observations. The net flow in the center of the basin ranges form 0 to up to 30 Sv depending of the wind structure. The values obtained for the heat transport, as given ranged from 0.40 to 0.81 PW with a mean value of 0.54 PW and a standard deviation of 0.11 PW. The total heat transport shows a pronounced increase from July 2004 to

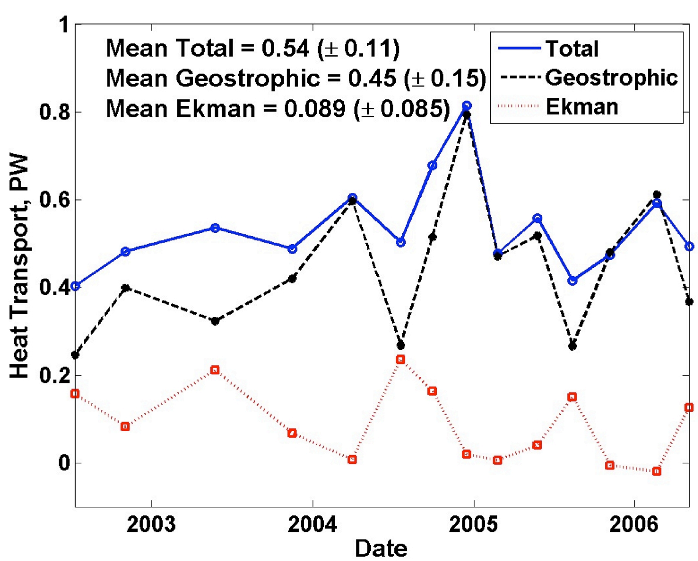

Figure 3: Variability with latitude of the computed total (red) and geostrophic (blue) fluxes. The lines are the linear fit between the total heat transport (red) and geostrophic heat transport (blue) with latitude.

December 2004 and a decrease thereafter (Figure 3). It also indicates some variability that may either be natural variability or may be related to the difference in cruise track. The variability of the transports is analyzed as a function of the mean latitude. Results indicate that there is no obvious relationship between the geostrophic transport (what is actually measured) and the latitude. Therefore, the long-term interannual variability (on the order of 0.4 PW peak to peak) is not convincingly driven by aliasing of the sections in space.

The total heat transport shows apparent interannual variability, but does not show a strong indication of seasonality. The percentage of variance explained by an annual cycle fit to the total transport is 24%, a value similar to the one observed in the model (31% at 30°S and 17% at 35°S). The scatter about the annual cycle fit is in some cases natural interannual variability, and in others is due to the difference in the cruise tracks. For example, the results from the two cruises conducted during the months of July 2002 and July 2004 yield values of 0.40 and 0.50 PW, respectively. In this case, the difference is due to the different routes because the July 2002 cruise was conducted at a mean latitude of 30° 19'S where the Ekman component of the flux is low (0.16 PW) while the 2004 cruise was conducted at a mean latitude of 36° 42'S where the Ekman component of the flux is high (0.24 PW). If only the geostrophic component of the flow is analyzed minimum values of the heat transport are observed for the period July to September (around day 200). In other words, the geostrophic component of the heat transport reaches its lowest values during the austral winter when the Malvinas Current reaches its northernmost latitude. There is only a slight indication that the values are higher during the austral summer (January, February, March) when the Brazil current reaches its southern extension and the Malvinas Current retreats to the South. The heat transport obtained from the POCM model (Baringer and Garzoli, 2006) contains a seasonal cycle similar to the one observed in the Ekman transports (same amplitude and phase). This indicates that in the model, most of the variability is due to Ekman flow while in the real ocean, the geostrophic component of the flux is an important component of the total flux.

The maximum observed value for heat transport is obtained during the month of December 2004, 0.81 PW, and it is mostly due to the geostrophic component (which has a value of 0.79 PW). Average SST anomalies during the cruise indicate a warm anomaly at the eastern boundary (+5°C). The vertical temperature profiles (not shown) indicate anomalously warm waters between 40° and 50°W extending from 100 to 500 m (with respect to climatology). Given the large seasonal and interannual variability, the huge influence of the variable wind field, and the different latitudes of the sections, many more observations would be needed to assess the seasonal cycle much less any climate trend from these observations.

Finally, to put the results from this analysis into context, results are compared (Figure 4) to the mean value of the heat transport obtained as the residual calculations from air sea flux in the Atlantic Ocean. The net heat transport obtained by Garzoli and Baringer (2007) (0.54 ± 0.11PW) is similar to the one obtained from the NCEP reanalysis and very close to the one obtained by Lumpkin and Speer (0.60 ± 0.08 PW, 2006) for the WOCE line A11. The high-density lines AX18 are to be continued at the rate of 4 per year. After a sufficient number of realizations, it is assumed that these heat transport estimates will become more robust. It is concluded that at these latitudes, the mean heat transport observed was 0.54 PW with an uncertainty of 0.18 PW.

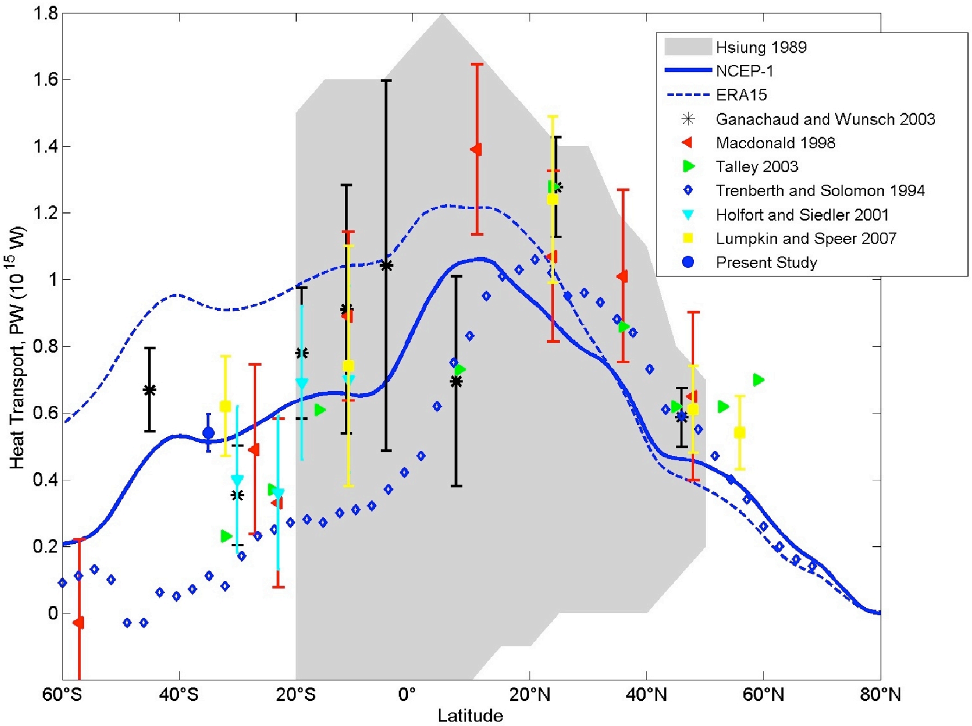

Figure 4: Oceanic Heat transport implied from integrating air-sea flux products (NCEP-1 and ERA15) starting from North Atlantic compared to several direct estimates of the heat transport from trans-basin sections (see legend). The AX18 mean heat transport (blue circle) compares favorably with the NCEP surface fluxes. The NCEP-1 annual mean was obtained from an average climatology of the years 1949 to 2003, (Kalnay, 1996). The ERA15 annual mean was derived from the ECMWF climatology based on 1979 – 1993, (Gibson *et al*., 1997)

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4. Garzoli, Silvia L. and Molly O. Baringer, 2007. Meridional Heat Transport using Expandable Bathythermographs Part II: South Atlantic Transport. *Deep Sea Research (Part 1)*, DOI information doi:10.1016/j.dsr.2007.04.013.

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2. Baringer M., S. Garzoli, G. J. Goni, C. Thacker and R. Lumpkin, 2006. Quarterly Reports on the State of the Ocean: Meridional Heat transport Variability in the Atlantic Ocean. In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 265-268.

3. Baringer, M.O., G.J. Goni, and S.L. Garzoli, 2006. Atlantic high-density XBT lines. In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 181-182.